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T1 Carbon Transmitter Model for Use in Computer-Aided Analysis of Telephone Set Transmission Characteristics

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A carbon transmitter model is presented, the purpose of which is to serve as a tool for computer-aided analysis of telephone set transmission characteristics. The derivation of the model is based upon the physical theory of the device. The parameters in the model are evaluated by comparing the analytically derived expressions for the device characteristics to the measured characteristics of a typical device. Because these parameters are related to the physical theory, the model not only serves its desired practical end, but also serves as a vehicle whereby an understanding is obtained of the relationship between device characteristics and physical theory.

I. INTRODUCTION

Computer-aided optimization of the transmission characteristics of telephone sets requires that accurate models be obtained for all transmission-related telephone set components. A carbon transmitter model has been derived for this purpose. This model has been used in a telephone set transmission analysis computer program, and good agreement between computed and measured transmission characteristics was obtained.

The dc V-I characteristic of the carbon transmitter is nonlinear. This nonlinearity must be taken into account in the dc model so that, in the transmission analysis program, the operating point of the transmitter can be determined, as well as the operating points of any nonlinear telephone speech network components, e.g., silicon carbide varistors. Thus, the dc model is a voltage-dependent resistance.

The ac model is similar to that of a vacuum-tube triode, consisting of a Thevenin-equivalent resistance and voltage source. The voltage source is dependent on the amplitude of the force acting on the carbon granules because of the acoustic excitation of the transmitter. This

force is in turn the output of a filter which represents the transmitter structure itself. The input to the filter is the acoustic sound pressure. This filter can he represented by an electrical equivalent circuit,[1] the derivation of which is straightforward. However, it is the characterization of the effects taking place within the carbon chamber which is of primary interest here. The filter is represented simply by its measured frequency response.

Values for the various parameters of the model were determined by comparing the expressions derived analytically for the characteristics of the transmitter to the measured characteristics of a typical device. All measurements were made with the transmitter face in a vertical plane, in a telephone handset, and in a position relative to the artificial mouth as specified in IEEE Standard 269-1971.[2] Also, the transmitter was mechanically and acoustically conditioned prior to the measurements. The acoustic conditioning signal was swept between 300 and 3300 Hz at a rate of six sweeps per second and frequency-weighted corresponding to the average sound pressure spectrum of continuous speech, and had an average sound pressure level of 94 dB (re 0.0002 dyn/cm^2). The conditioning signal was applied for 3 s.

II. DC MODEL

As shown in Fig. 1, the dc V-I characteristic of the carhon transmitter is nonlinear. Goucher[3] attributed the nonlinearity to the effect of joule heating on the contact resistance between carbon granules. Later, Mol,[4] disputing Goucher, attrihuted the nonlinearity to the

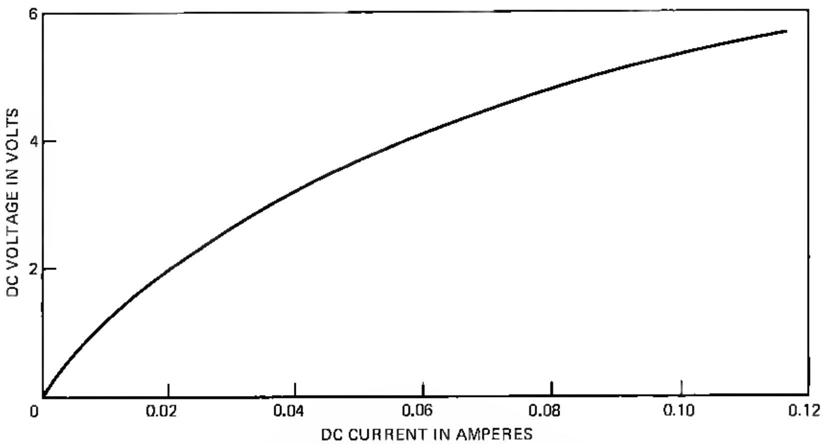

Fig. 1—Direct-current V-I characteristic.

effect of electrostatic forces between carbon granules. On this basis, he derived an expression for the dc transmitter resistance as a function of voltage and found it to agree fairly well with measured transmitter resistance. However, Mol's expression for the dc voltage dependence of the resistance variation when an acoustic signal acts on the transmitter agrees rather poorly with measurement. This casts doubt on the electrostatic force theory. In fact, experimental results indicate that the effect of electrostatic forces between carbon granules is negligible. These experiments are described in Appendix A. On the other hand, a more recent study of the theory of electric contacts tends to support Goucher's theory. Holm[5] treats the subject of the effect of joule heating on contact resistance extensively, and his results will be applied to the derivation of the transmitter model.

As will be seen, the nonlinearity of the V-I characteristic cannot be accounted for entirely by the effect of joule heating on contact resistance. The effect of the thermal expansion of the carbon chamber due to joule heating must also be considered. This effect is readily demonstrated experimentally because of the relatively long time constant involved. If the transmitter current is changed abruptly, a slowly decaying voltage transient is observed, owing to the hysteresis associated with the expansion of the carbon chamber. The time constant is approximately 1 s.

A cross section of the T1 transmitter is shown in Fig. 2. The carbon chamber consists of a movable dome electrode connected to a fixed conical back electrode by a flexible, nonconducting chamber closure. According to the results of Fritsch's analysis[6] of the thermal response of the transmitter structure, the transient effect is due primarily to the expansion of the dome electrode. As the dome electrode expands, it compresses the carbon granules, lowering their resistance. Fritsch called this effect "thermal packing." Of course, after the transient has decayed, the transmitter can be reconditioned to unpack the granules. However, following the reconditioning, a new thermal equilibrium will be established so that some degree of thermal packing will still occur. This effect, as well as the effect of joule heating on contact resistance, must be included in the model. An understanding of these effects is based on a consideration of the factors affecting the resistance of a single carbon contact.

2.1 Effect of contact force on contact resistance

The contact resistance between two carbon granules is related to the magnitude of the force pressing the granules together by the expression:

$$r_k = KP^{-\gamma}, \tag{1}$$

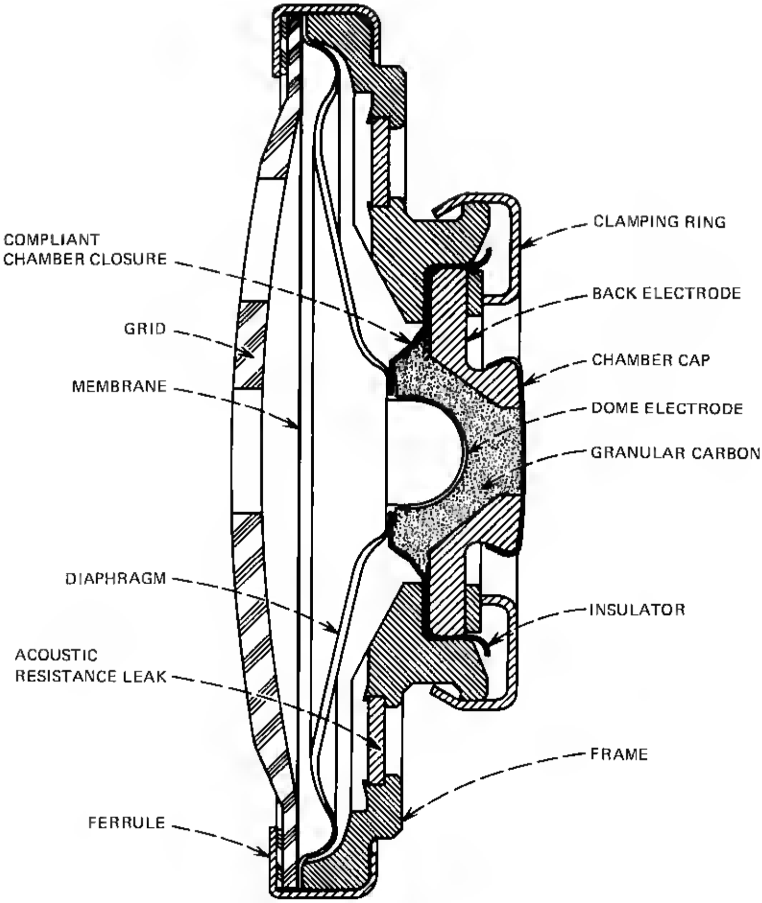

Fig. 2—Cross section of T1 transmitter.

where P is the contact force and K and γ are constants. Equation (1), which is generally valid for electric contacts, was shown by Goucher[3] to be valid for carbon granules, based on direct measurement of contact resistance and force. Later, this equation was indirectly shown by Joscheck[7] to be valid based on measurements of the bulk resistance of carbon granules as a function of the filling height of the granules in the measurement chamber.

In the carbon chamber in the T1 transmitter, the significant forces acting on the carbon granules are the gravitational force resulting from the weight of the granules themselves, the force resulting from the thermal expansion of the dome electrode, and, when the transmitter is acoustically excited, the force resulting from the acoustic

pressure acting on the diaphragm and dome electrode. Because of the random orientation of the contacts throughout the chamber with respect to the directions of the applied forces, the contact force and, hence, the contact resistance will also vary randomly. However, because of the large number of contacts involved, the random variation in contact resistance can be ignored. Only the larger overall gradients in bulk resistivity will be considered.

For simplicity, an approximate chamber geometry is assumed in which the two electrodes are concentric hemispheres. A spherical coordinate system is defined such that the hemispherical chamber walls lie at constant radial distances from the origin, the inner and outer radii being designated a and b, respectively. The component of contact force resulting from the weight of the granules themselves is represented by $P_g(r, \theta, \phi)$. The component resulting from the thermal expansion of the dome electrode, being proportional to the power dissipated by the transmitter, is represented by $(V^2/R) P_d(r, \theta, \phi)$, where V and R are the transmitter dc voltage and resistance, respectively. The component resulting from the acoustic excitation of the transmitter, being a function of time as well as of the spatial coordinates, is represented by $\Delta P(r, \theta, \phi, t)$.

Equation (1), therefore, becomes

$$r_k(r, \theta, \phi, t) = K[P_g(r, \theta, \phi) + (V^2/R)P_d(r, \theta, \phi) + \Delta P(r, \theta, \phi, t)]^{-\gamma}. \quad (2)$$

It will subsequently be seen that, for normal speech signal levels, ΔP is small enough compared to the static components of contact force that its effect on the dc component of contact resistance is negligible. Thus, the relationship between the dc contact resistance and the contact force is

$$r_k(r, \theta, \phi) = K[P_g(r, \theta, \phi) + (V^2/R)P_d(r, \theta, \phi)]^{-\gamma}. \quad (3)$$

Although a change in dc transmitter resistance is observed when acoustic excitation is applied to the transmitter, this is judged to be due to the effect of the acoustic excitation on the state of compactness of the carbon granules rather than to the effect of the nonlinearity of the contact resistance–contact force characteristic. The effect of acoustic excitation on the state of compactness of the granules will be discussed further.

2.2 *Effect of joule heating on contact resistance*

According to Holm's analysis[5] of the effect of joule heating on contact resistance, if certain assumptions regarding the temperature

dependence of the electrical resistivity and the thermal conductivity of the contact memhers are satisfied, then the effect of joule heating can be accounted for by multiplying the contact resistance by the factor

$$\eta(V_k) = [B + (1 - B)(A_k/V_k)\tan^{-1}(V_k/A_k)]^{-1}, \tag{4}$$

where V_k is the contact voltage and A_k and B are constants. Since the random variation in contact voltage is of no concern in the model, V_k is considered to he the average contact voltage, which is proportional to the total transmitter voltage. Then

$$\eta(V) = [B + (1 - B)(A/V)\tan^{-1}(V/A)]^{-1}, \tag{5}$$

where A is also a constant.

The assumptions upon which the derivation of eq. (4) is based are that the thermal conductivity satisfies

$$\lambda = \lambda_0(1 + \beta\Delta T), \tag{6}$$

and the electrical resistivity satisfies

$$\rho = \rho_0(1 + \epsilon\Delta T)/(1 + \beta\Delta T), \tag{7}$$

where ρ_0, λ_0, ϵ, and β are constants, and ΔT is the change in temperature because of joule heating. Apparently, these assumptions are valid in this case hecause of tbe excellent agreement hetween eq. (5), using the values for A and B, listed suhsequently, and the measured data presented by Hufstutler and Kerns[8] for the resistivity of granular carbon contained in a quartz test chamher having a negligible thermal expansion coefficient. This implies that, aside from the effect of chamber expansion, the effect of joule beating on contact resistance is alone sufficient to account for the nonlinearity of the V-I characteristic.

Now, if eqs. (5) and (3) are comhined, the expression for the dc contact resistance becomes

$$r_k(r, \theta, \phi) = K\eta(V)[P_s(r, \theta, \phi) + (V^2/R)P_d(r, \theta, \phi)]^{-\gamma}. \tag{8}$$

2.3 Total dc resistance

If $r_k(r, \theta, \phi)$ is the contact resistance and there are n contacts per unit length, then the resistivity of the carbon granules is $r_k(r, \theta, \phi)/n$, where $r_k(r, \theta, \phi)$ is given by eq. (8). Then, for the approximate chamber geometry which has heen assumed, the total dc transmitter resistance is

$$R = \int_a^b \frac{dr}{r^2 \int_0^\pi \int_0^\pi [n \sin\phi / r_k(r, \theta, \phi)] d\phi d\theta}. \tag{9}$$

The mean value theorem can be applied to perform the integrations

with the result

$$R = R_0\eta(V)[1 + \alpha V^2/R]^{-\gamma}, \tag{10}$$

where

$$R_0 \equiv K(b - a)/[n\pi^2\bar{r}^2 \sin \bar{\phi} P_g{}^{\gamma}(\bar{r}, \bar{\theta}, \bar{\phi})], \tag{11}$$

$$\alpha \equiv P_d(\bar{r}, \bar{\theta}, \bar{\phi})/P_g(\bar{r}, \bar{\theta}, \bar{\phi}), \tag{12}$$

and where $\bar{r}$, $\bar{\theta}$, and $\bar{\phi}$ are constants, heing the coordinates of some point within the chamher. Note that R_0 is the limiting value of R as V approaches zero, and that $\alpha V^2/R$ is the average ratio of the component of contact force due to thermal expansion of the carhon chamher to the component of contact force due to the weight of the granules themselves. Although R is not expressed as an explicit function of V, a solution to eq. (10) can he ohtained using iterative techniques easily implemented on the computer. Values for the parameters R_0, α, A, B, and γ will he determined hy fitting eq. (10) simultaneously with equations for the transmitter ac resistance and open circuit output voltage to measured data. The ac resistance and open circuit output voltage will now be considered.

III. SMALL-SIGNAL AC RESISTANCE

Over the range of frequencies of interest for speech transmission, the transmitter ac impedance is purely resistive. However, as is ohvious from Fig. 3, the ac resistance is not the slope of the dc V-I characteristic except in the limit as V approaches zero. This is explained by the fact that, hecause of the large hysteresis effect, the thermal expansion of the dome electrode cannot follow the ac signal, at least not at frequencies above a few hertz. Thus, the difference hetween the ac resistance, which is not affected hy the thermal expansion of the dome electrode, and the slope of the dc V-I characteristic, which is affected, increases as the power dissipated hy the transmitter increases.

Because the thermal expansion of the dome electrode has no effect on the ac resistance, the ac resistance is the slope, not of the actual V-I characteristic, hut of the V-I curve defined hy setting the term equal to zero which accounts for the expansion of the dome electrode. This is the curve defined hy

$$I = V/[R_0\eta(V)], \tag{13}$$

where R_0 and $\eta(V)$ are defined hy eqs. (11) and (5), respectively. Thus, the ac resistance is given hy

$$\begin{aligned} r_{ac} &= R_0\eta^2(V) \Big/ \left[\eta(V) - V\frac{d}{dV}\eta(V)\right] \\ &= R_0(A^2 + V^2)/(A^2 + BV^2). \end{aligned} \tag{14}$$

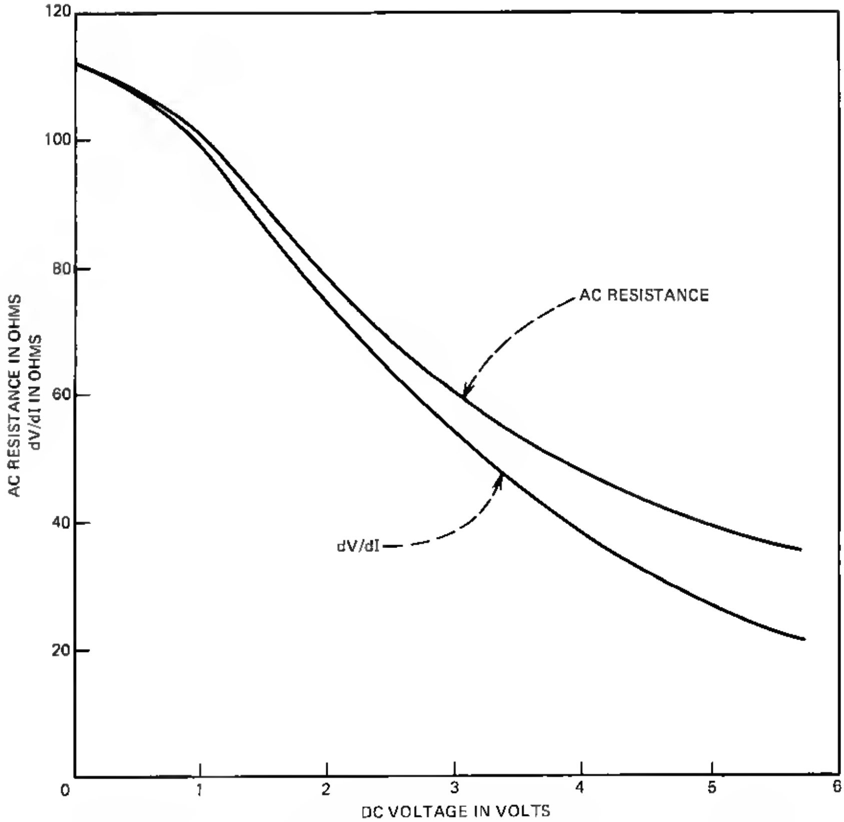

Fig. 3—Alternating-current resistance characteristic and slope of dc V-I characteristic.

It has been assumed that the ac signal level is low enough so that there is no significant joule heating effect due to the ac signal. This assumption is valid for signal levels typical of speech transmission. For higher signal levels, tbe ac joule heating effect will cause the ac as well as the dc resistance to decrease, as is easily verified experimentally.

At frequencies low enougb that the period of the ac signal becomes significant compared to the time constant associated with tbe thermal response of the dome electrode, the transmitter ac impedance exhibits a reactive component due to the effect of the thermal hysteresis. Figure 4, drawn from a photograph of a storage oscilloscope trace, shows the effect of the thermal hysteresis in the response to a sinusoidal driving voltage at a frequency of 0.2 Hz for four different operating points. The effect becomes greater as the dc bias increases, as would

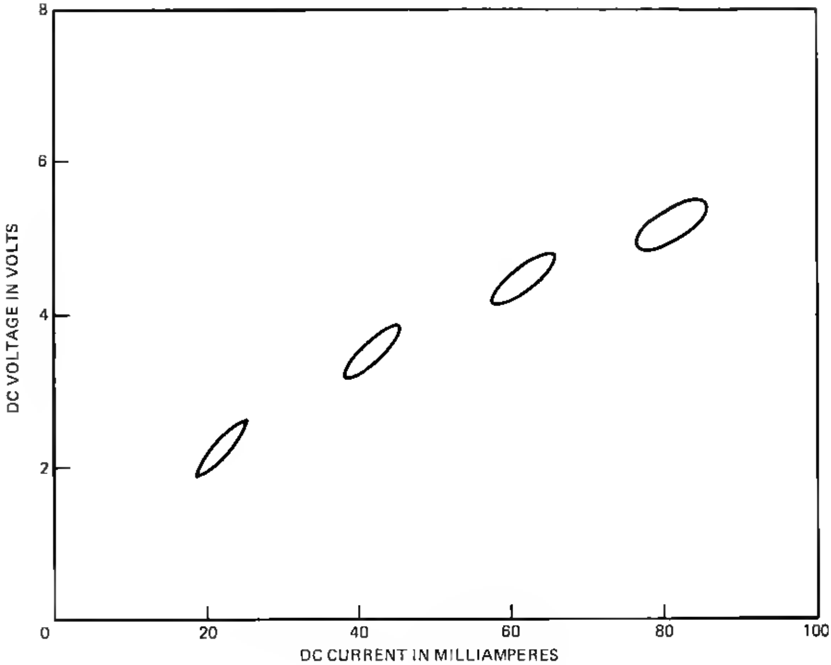

Fig. 4—Thermal hysteresis effect at 0.2 Hz.

be expected since the expansion of the dome electrode is proportional to the power dissipated by the transmitter. An expression for the low-frequency transmitter impedance that accounts for this effect is derived in Appendix B. For frequencies greater than approximately 10 Hz, the reactive component of the transmitter impedance becomes negligible, and the expression derived in Appendix B reduces to the expression given by eq. (14).

IV. OPEN-CIRCUIT OUTPUT VOLTAGE

When the transmitter is acoustically excited, the contact force will vary owing to the effect of the acoustic pressure acting on the diaphragm and dome electrode. The variation in the contact force at the point (r, θ, ϕ) is designated $\Delta P(r, \theta, \phi, t)$. Then the resistance will vary by an amount $\Delta R(t)$ such that

$$R + \Delta R(t) = R_0 \eta(V)[1 + \alpha V^2/R + \overline{\Delta P}(t)]^{-\gamma}, \tag{15}$$

where

$$\overline{\Delta P}(t) \equiv \Delta P(\bar{r}, \bar{\theta}, \bar{\phi}, t)/P_g(\bar{r}, \bar{\theta}, \bar{\phi}). \tag{16}$$

The transmitter voltage will change by an amount $\Delta V(t)$ where, if the transmitter current I is beld constant,

$$V + \Delta V(t) = I[R + \Delta R(t)]. \tag{17}$$

Then

$$\begin{aligned} \Delta V(t) &= I\Delta R(t) \\ &= V\Delta R(t)/R, \end{aligned} \tag{18}$$

which is the ac open-circuit output voltage. From eq. (15),

$$\Delta R(t)/R = [1 + \overline{\Delta P(t)}/(1 + \alpha V^2/R)]^{-\gamma} - 1, \tag{19}$$

so that

$$\Delta V(t) = V\{[1 + \overline{\Delta P(t)}/(1 + \alpha V^2/R)]^{-\gamma} - 1\}. \tag{20}$$

Although this is a nonlinear relationship, $\overline{\Delta P}(t)$ will be found to be small enough compared to $1 + \alpha V^2/R$ at normal speech levels so that a linear approximation is justified. Thus,

$$\Delta V(t) \approx -\gamma V\overline{\Delta P}(t)/(1 + \alpha V^2/R). \tag{21}$$

Note that eq. (21) is $-\gamma V$ multiplied by the ratio of the dynamic to the static forces acting on the carbon granules.

V. EVALUATION OF MODEL PARAMETERS

The parameters R_0, α, γ, A, B, and $\overline{\Delta P}(t)$ were evaluated using an iterative optimization computer program to fit eqs. (10), (14), and (21) simultaneously to measured dc resistance, ac resistance, and open-circuit output voltage, respectively, the latter being measured at a frequency of 1 kHz with a sound pressure level of 94 dB (re 0.0002 dyn/cm^2). The measurements were performed on a T1 transmitter considered to be a typical unit. The resulting parameter values are listed in Table I. Of course, transmitter characteristics are subject to such factors as aging, temperature, conditioning, orientation, and manufacturing variations. The values of the parameters in eqs. (10), (14), and (21) will vary accordingly.

Table I — Parameter values

Parameter	Value
R_0	111.0
α	0.94
γ	0.43
A	7.12
B	6.65
$\overline{\Delta P}$(rms)	0.20

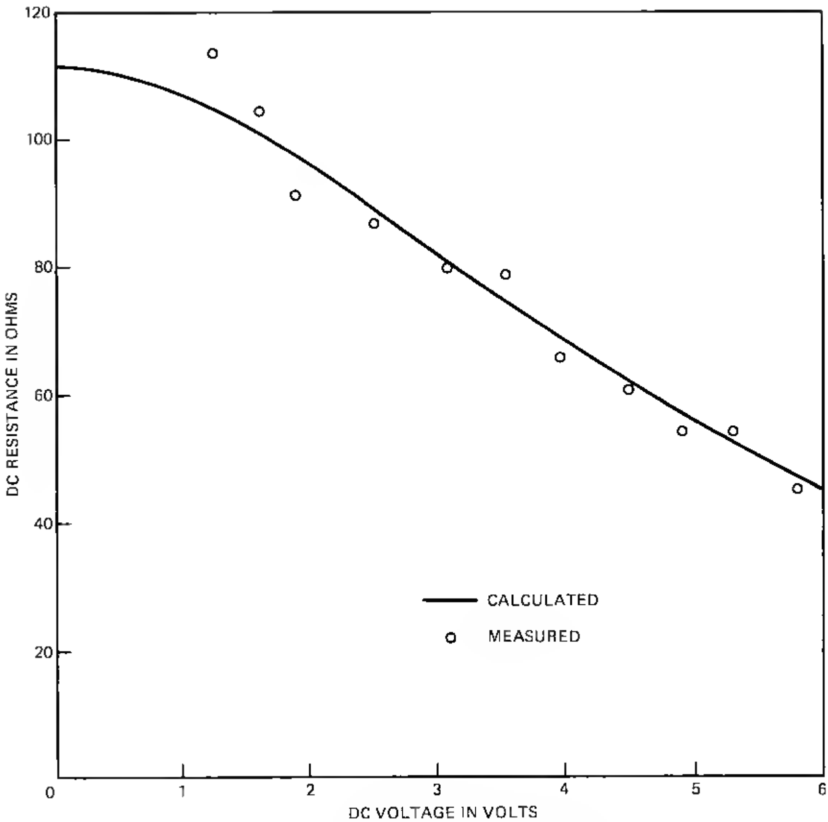

Fig. 5—Direct-current resistance characteristic.

Equations (10), (14), and (21), with the parameter values listed in Table I, are plotted in Figs. 5, 6, and 7, respectively, along with measured data points. The agreement between calculated and measured data is judged to be within the limits of measurement error.

VI. INPUT-OUTPUT AND FREQUENCY RESPONSE CHARACTERISTICS

To complete the model, the input-output and frequency response characteristics of the transmitter must be specified. The input-output characteristic is nonlinear owing to the effect of the acoustic excitation on the compactness of the carbon granules. As the acoustic signal level increases, the carbon granules are agitated into a less compact state and the mechanical impedance of the granules decreases. Therefore, the transmitter efficiency increases as the acoustic signal level increases, resulting in an input-output characteristic having a greater-

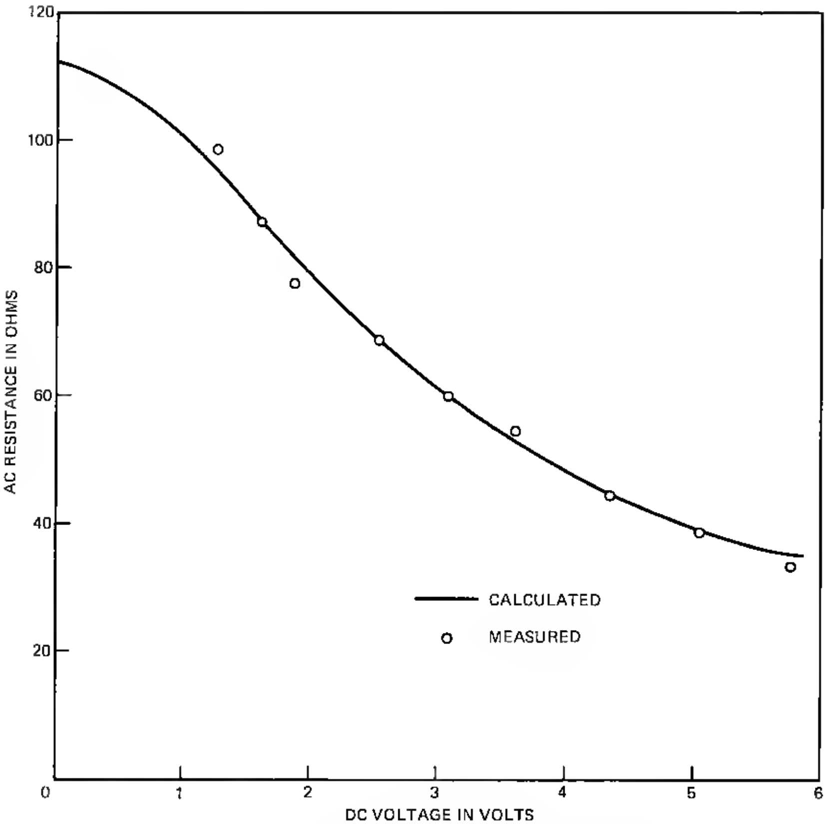

Fig. 6—Alternating-current resistance characteristic.

than-unity slope. Because of this effect, the transmitter is able to discriminate against distant sounds, and thereby reduce interference resulting from background noise. However, the weak components in a composite signal such as speech are not discriminated against, since the compactness of the carbon granules, which is controlled by the strong components, is the same for all components of the signal. Therefore, the nonlinearity of the input-output characteristic does not affect the components of individual speech sounds, and the compactness of the carbon granules varies only as the overall energy content of the speech signal varies.

As discussed by Bryant,[9] the frequency response of the transmitter is related to the nonlinearity of the input-output characteristic, since it also depends on the mechanical impedance of the carbon granules. This implies that the frequency response depends on the nature of the input signal. The response to a swept frequency sinusoidal signal is

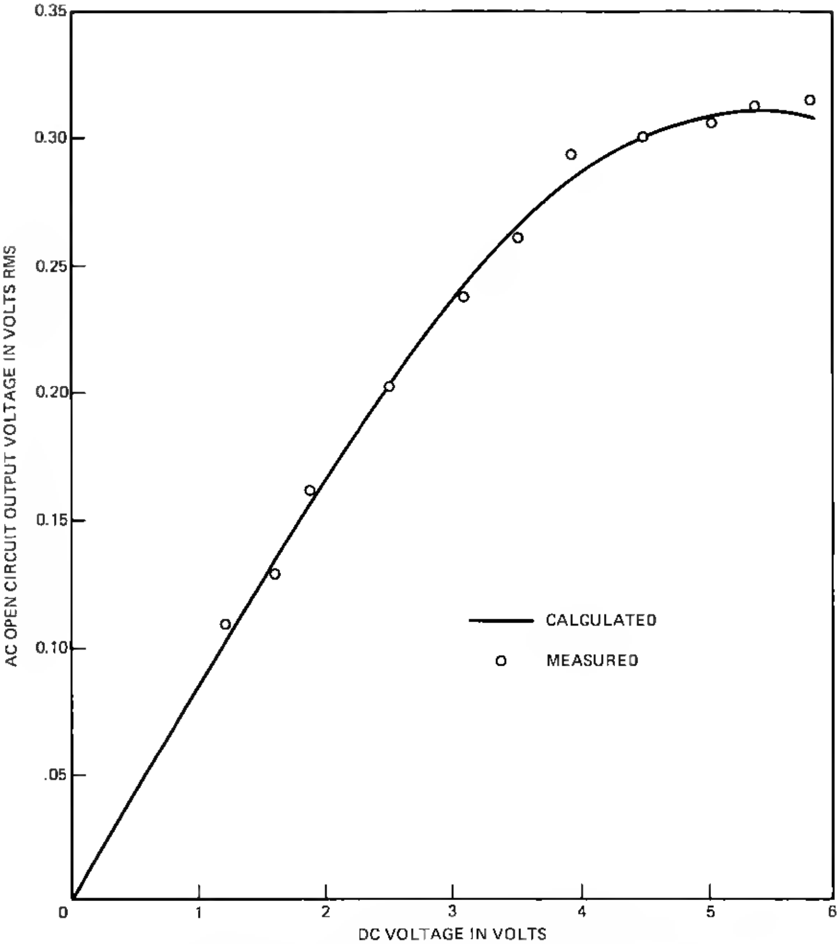

Fig. 7—Alternating-current open-circuit output voltage characteristic at 1 kHz for a 94-dB (re 0.0002 dyn/cm^2) acoustic input level.

somewhat different from the response to a speech signal. (For further discussion, see Ref. 9.)

For the purposes of the model, a continuous, random, speech input signal is assumed. Accordingly, the nonlinearity of the input-output characteristic is ignored, and the frequency response is measured as suggested by Bryant. The response is shown in Fig. 8 plotted relative to the 1-kHz output level. This is the response of the transmitter structure itself to the acoustic input signal, or, in the model, the response of the input filter. In the computer program, the filter response was stored as a tahle of values at discrete values of frequency.

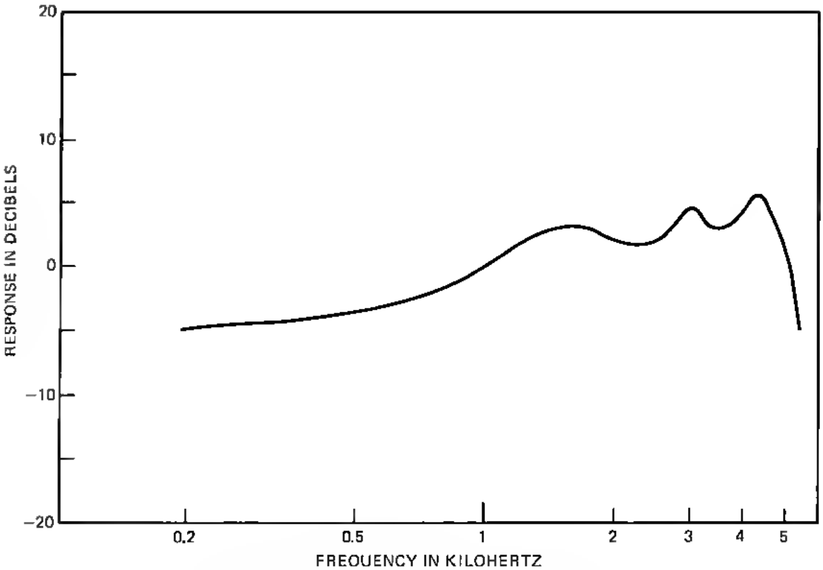

Fig. 8—Transmitter gain (relative) vs frequency.

VII. CONCLUSION

A carhon transmitter model has heen presented. The physical theory upon which the model is hased is supported hy the close agreement between the calculated characteristics of the model and the measured characteristics of an actual device. Thus, it can he concluded that the nonlinearity of the dc V-I characteristic is due primarily to the effect of joule heating on contact resistance and to the effect of the thermal expansion of the dome electrode due to joule heating. The effect of electrostatic forces is negligihle. Furthermore, the difference hetween the ac resistance and the slope of the dc V-I characteristic is due to the hysteresis associated with the thermal expansion of the dome electrode. Finally, the relative resistance change due to the acoustic excitation of the transmitter decreases as the dc voltage increases due also to the effect of the thermal expansion of the dome electrode.

VIII. ACKNOWLEDGMENT

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APPENDIX A

In this appendix, the question is considered of whether electrostatic forces hetween carhon granules have a significant effect on transmitter

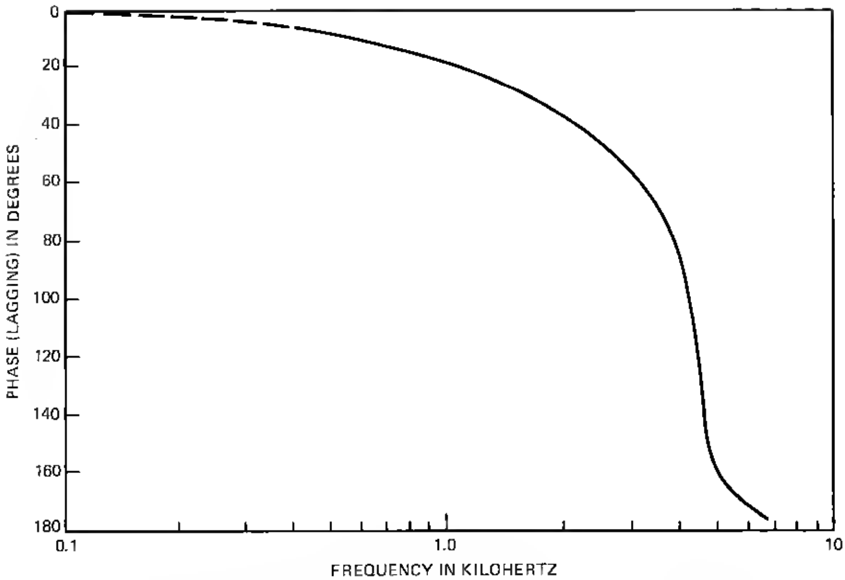

Fig. 9—Phase of diaphragm displacement resulting when transmitter output is driven by sinusoidal ac voltage.

characteristics. Two experiments, the results of which indicate that they do not, are described. In both experiments, the transmitter output is driven with a sinusoidal voltage, i.e., as if the transmitter were a receiver. It is observed that, if the transmitter is driven hard enough, an audible signal is generated. Approximately 2-V rms is required for the signal to be audible at 1 kHz. This phenomenon could be the result of attractive forces between carbon granules owing to electric fields or the result of thermal expansion, presumably of the carbon granules, since the thermal inertia of the dome electrode and diaphragm is too large for their thermal response to follow the instantaneous voltage at frequencies above a few hertz. The results of the two experiments which are now described indicate that the forces are due to thermal expansion of the carbon granules. This effect is insignificant compared to the predominant thermal effects that are accounted for in the model.

In the first experiment, the phase of the dome electrode displacement was measured. An outward displacement, in phase with the square of the driving voltage at frequencies far enough below resonance so that the mass of the system can be ignored, would indicate that the force was due to thermal expansion, while an inward displacement would indicate that the force was due to electric fields. The displacement was measured using an optical proximity detector. A small mirror was mounted on the dome electrode to provide a flat reflecting surface

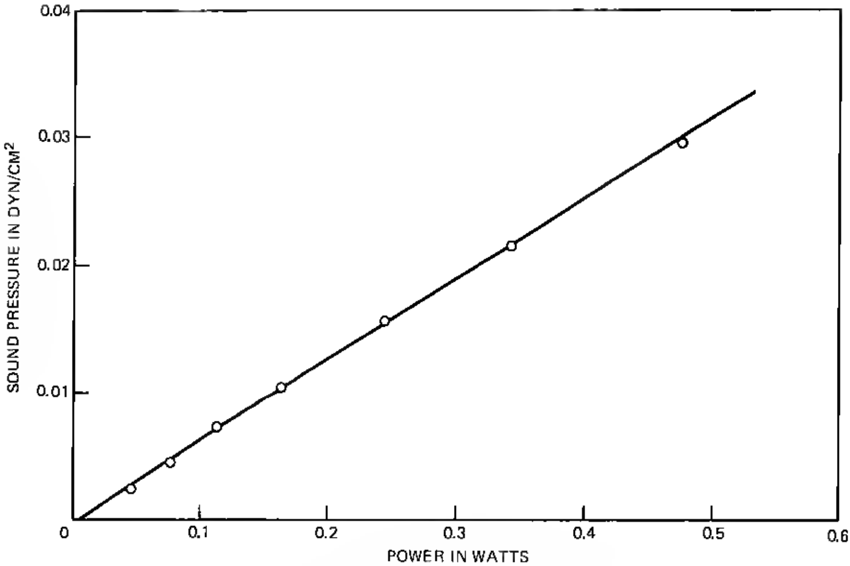

Fig. 10—Output sound pressure—input power characteristic resulting when transmitter output is driven by sinusoidal ac voltage.

for the detector. This was necessary to obtain measurable detector output, the displacement being very small. The phase of the outward displacement relative to that of the square of the driving voltage is plotted as a function of frequency in Fig. 9. The phase angle approaches zero at low frequencies, indicating that the force acting on

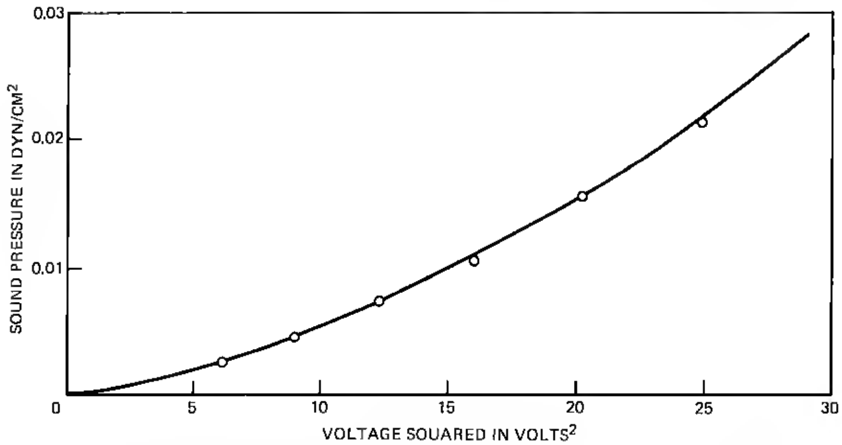

Fig. 11—Output sound pressure—input voltage squared characteristic when transmitter output is driven by sinusoidal ac voltage.

the dome electrode is due to the thermal expansion of the carbon granules.

Since this is the case, the acoustic sound pressure level should he proportional to the power dissipated hy the transmitter rather than the square of the voltage, as would he the case if the forces were due to electric fields. (Power is not proportional to the square of the voltage, since the resistance is a function of voltage.) This was verified hy the second experiment, the results of which are plotted in Figs. 10 and 11.

APPENDIX B

In this appendix, an expression is derived for the low-frequency impedance of the transmitter, taking into account the effect of the thermal expansion of the carbon chamber.

If the transmitter current is changed abruptly hy an incremental amount ΔI, the displacement of the dome electrode due to the additional power dissipation will lag hehind the change in current due to the thermal hysteresis. According to Fritsch's analysis,[6] the transient can be expressed as an infinite sum of decaying exponentials. Thus,

$$\Delta V(t) = (m + \sum_{i=1}^{\infty} k_i e^{-t/\tau_i}) \Delta I u(t), \tag{22}$$

where m is the slope of the dc V-I characteristic and where k_i and τ_i are constants. Because the initial change in voltage must be $r_{ac}\Delta I$,

$$\sum_{i=1}^{\infty} k_i = r_{ac} - m. \tag{23}$$

In the frequency domain,

$$\Delta V(s) = [m + \sum_{i=1}^{\infty} k_i s/(s + 1/\tau_i)] \Delta I/s, \tag{24}$$

from which

$$Z(s) = m + \sum_{i=1}^{\infty} k_i s/(s + 1/\tau_i). \tag{25}$$

As pointed out hy Fritsch,[6] the infinite series solution converges too slowly for practical evaluation. A practical expression for ac impedance can he ohtained hy assuming a single time-constant approximation for the transient response. Then

$$Z(s) \approx m + ks/(s + 1/\tau), \tag{26}$$

where τ is the effective time constant and

$$k = r_{ac} - m. \tag{27}$$

If eq. (27) is substituted into eq. (26), then

$$Z(s) \approx r_{ac}(s + m/r_{ac}\tau)/(s + 1/\tau). \tag{28}$$

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